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Cascade Reactor Concept For Neutron Multiplication of Subcritical Core

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A "cascade reactor concept" represents a kind of system with an accelerator driven subcritical core consisting of two sections with different neutron spectra. It can generate more neutrons than one-section fast core with the same subcriticality and the same neutron source strength.

This study deals with the effect of the cascade reactor concept by analogy of a coupling core and direct simulation using a Monte Carlo code. The proton energy is assumed to be 1.0 GeV and a Pb-Bi target is at the center of the core. The cascade reactor has two sections. The inner section is a fast flux core and the outer section is a thermal flux core. There is a neutron absorber between two sections. As the result of direct simulation, the cascade reactor concept is confirmed to generate twice as many neutrons as a one-section reactor with the same neutron source. It is found that the thickness of fast core should be small to enhance the cascade effect, the thickness of Sm absorber is optimized to be 5 cm and that cascade effect increases when the subcriticality becomes small. These results are consistent with the basic theory of coupling core.

KEYWORDS: Cascade reactor, accelerator driven subcritical core, neutron multiplication, MCNPX

1. Introduction

A cascade reactor is an innovative concept of accelerator driven subcritical core. Loading with MA increases positive void reactivity and reduces Doppler reactivity in fast reactors. One countermeasure against this problem is a system of an accelerator driven neutron source and a subcritical core. This system is easy to stop and remains subcritical enough at any reactivity inserted abnormal incidence.

A large power subcritical reactor needs an unprecedented large power accelerator and the energy balance becomes poor. For example, neutron source has to supply 5 % of fission neutrons when subcriticality is 5 %Δk. This problem is one of the incentives for the cascade reactor. The cascade reactor can make the neutron source smaller under the same subcriticality and the same power as a conventional one-section reactor. That is, it can generate more neutrons than a one-section reactor with the same subcriticality and the same neutron source.

Another feature of the cascade reactor is that there are both fast spectrum core and thermal spectrum core in itself. This is an advantage for a transmutation core because a different spectrum can be selected for each nuclide to be transmuted with fast reactors for long-lived fission products transmutation; moderator is often introduced to promote the transmutation ratio. The above thermal spectrum core has the same capability.

A cascade reactor concept was introduced by V. F. Koloesov and B. Y. Guzhovskii[1], V. F. Koloesov , S. K. Shtarev, V. K Khoruzhii, A. K. Zhithik[2], and P. N. Alekseev[3].

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These works indicate the potential of the coupled core theoretically. H. Sekimoto and M. Okamoto tried to apply this concept to an MA transmutation system with a Pb-Bi coolant core (fast core) and a light water coolant core (thermal core) [4] and calculated the effect of neutron multiplication, using ATRAS [5]. Yousry Gohar, Temitope A. Taiwo, James E. Cahalan, and Phillip J. Fink investigated the transmutation of radioactive waste based on an accelerator driven subcritical cascade core [6]. The core of their concept is a Helium cooled core with fast flux region and thermal flux region.

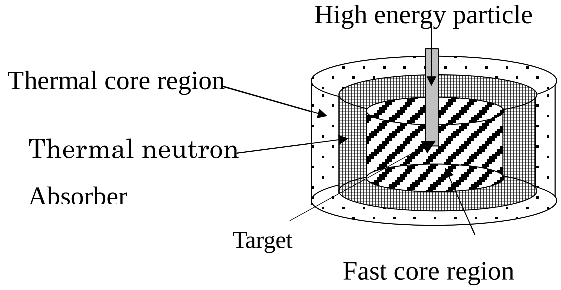

Fig.1 Configuration of Cascade Reactor

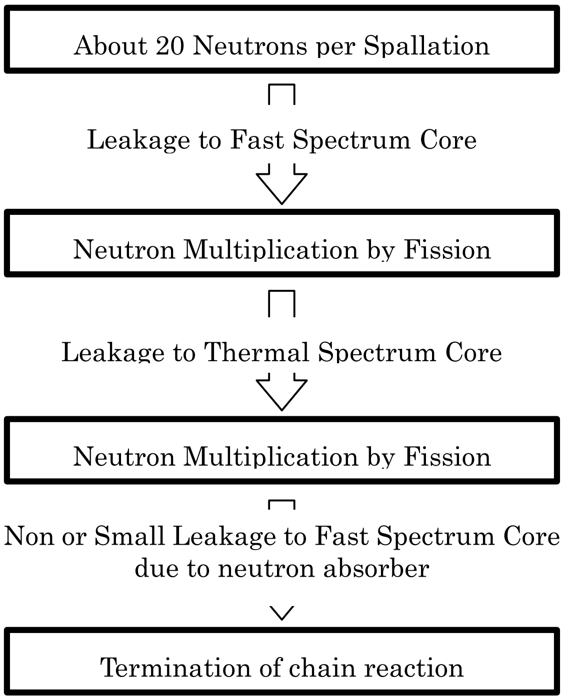

Fig. 2 Process for Cascade Reactor

We confirmed the feasibility of cascade concept in the previous work [7]. This paper is the analyses of the cascade reactor with analogy of the coupling core, performing several direct numerical calculations with the Monte Carlo code, MCNPX [8]. In section 2, neutron balance of the cascade reactor and a numerical relation of the characteristics regarding to neutron multiplication are discussed. Method for direct simulation of the cascade reactor is explained in section 3 and its result in section 4.

2. Basic Physics of Cascade Reactor

The cascade reactor has an accelerator driven neutron source and two separated cores as shown in Fig.1. Fig.2 explains event flow in the cascade reactor. Protons of 1.0 GeV collide with a heavy metal target and produce many high-energy neutrons by spallation reaction. These neutrons leak out to the fast spectrum section and induce fission reactions, and fission neutrons are produced. Some neutrons leave for the thermal spectrum section and generate fission neutrons again. The cascade reactor has a neutron absorber between two sections. This absorber captures thermal neutrons selectively so as to avert neutron leakage from the thermal core to the fast core.

The cascade reactor is a kind of coupling core and can be explained from physics of coupling reactor. The neutron balance equation for coupling core is as follows.

$$\begin{pmatrix} k11 & k12 \\ k21 & k22 \end{pmatrix}\begin{pmatrix} s1 \\ s2 \end{pmatrix} = k\begin{pmatrix} s1 \\ s2 \end{pmatrix} \qquad (1)$$

where

kij: multiplication factor in the i-th section for neutrons produced in the j-th section

k: multiplication factor of total coupling core

si: neutrons produced in the i-th section i:1/fast spectrum core, 2/thermal spectrum core

The following is obtained from Equation (1).

$$(k11-k)(k22-k)=k21k12 \quad (2)$$

That is,

$$k = 0.5 * \{(k11 + k22) \pm \sqrt{(k11 - k22)^2 + 4k12k21}\} \quad (3)$$

When an external source so exists, the neutron balance for the cascade reactor is presented as follows.

$$\begin{pmatrix} k11 & k12 \\ k21 & k22 \end{pmatrix}\begin{pmatrix} s1 \\ s2 \end{pmatrix} + \begin{pmatrix} s0 \\ 0 \end{pmatrix} = \begin{pmatrix} s1 \\ s2 \end{pmatrix} \quad (4)$$

Thus, the eigen-vector (s1, s2) becomes

$$\begin{pmatrix} s1 \\ s2 \end{pmatrix} = \frac{1}{(k11-1)(k22-1)-k21k12} \times \begin{pmatrix} (1-k22)s0 \\ k21s0 \end{pmatrix} \quad (5)$$

Total neutron production s is expressed as

$$s = \frac{(1-k22+k21)so}{(k11-1)(k22-1)-k21k12} \quad (6)$$

Alternatively,

$$s = \frac{(\Delta k2 + k21)}{\Delta k1 + \Delta k2 - \Delta k} \frac{s0}{\Delta k} \quad (7)$$

where $\Delta ki = 1-kii$, $\Delta k = 1-k$

Cascade effect coefficient f is defined as neutron production ratio of the cascade reactor to the one-section reactor.

$$f = \frac{(\Delta k2 + k21)}{\Delta k1 + \Delta k2 - \Delta k} \quad (8)$$

Fig. 3 presents combinations of k12 and k21 when the cascade effect coefficient f = 1.5, 2.0, 3.0 and 5.0 at subcriticality of 5 %Δk. To get the cascade effects coefficient of 2.0 (f =2.0), k12 has to be below 1/10 of k21. To improve the cascade effects up to 3.0 (f =3.0), k12 is to be reduced down to 1/30 of k21 at least.

In thermal reactors, fission neutron energy is about 2.0 MeV and 20 % of the fission reaction is by non-thermal

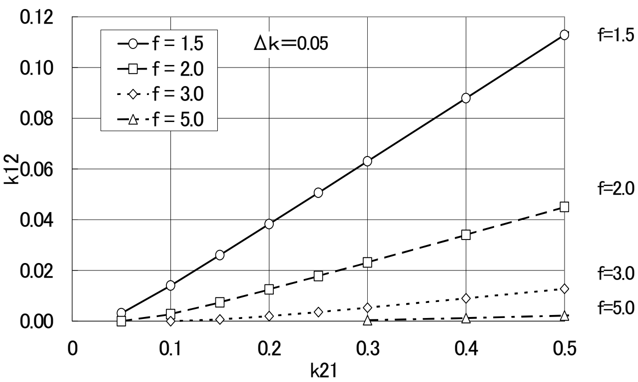

Fig. 3 *k12* and *k21* at constant cascade effect

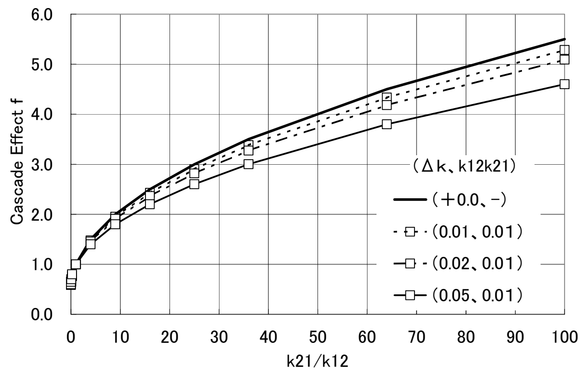

Fig. 4 Dependency of Cascade Effect

neutrons. Therefore it seems difficult that k12/k21 is below 1/100 and the cascade effect may be limited by this factor, when the cascade reactor is the above combination of the fast spectrum core and the thermal spectrum core like a light water reactor.

Fig. 4 shows dependency of the cascade effect on subcriticality. The expression (+0.0, -) indicates that it is near criticality boundlessly. As said above, when the subcriticality shifts to a small side (ex. from 0.05 to 0.01), the cascade effect increases somewhat (ex. by 5-15%), but it is not so large.

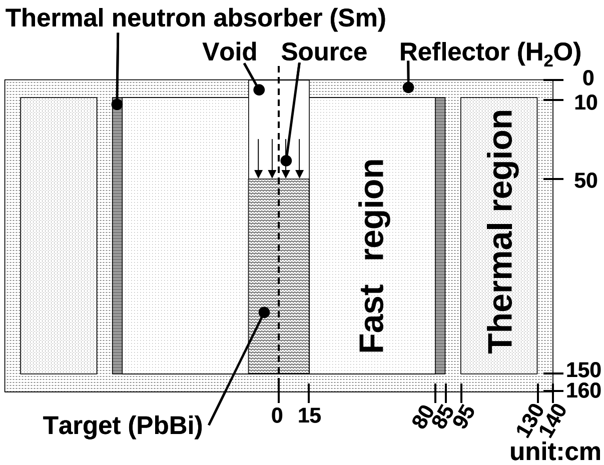

Fig. 5 Configuration of Cascade Reactor

3. Method for Numerical Analyses

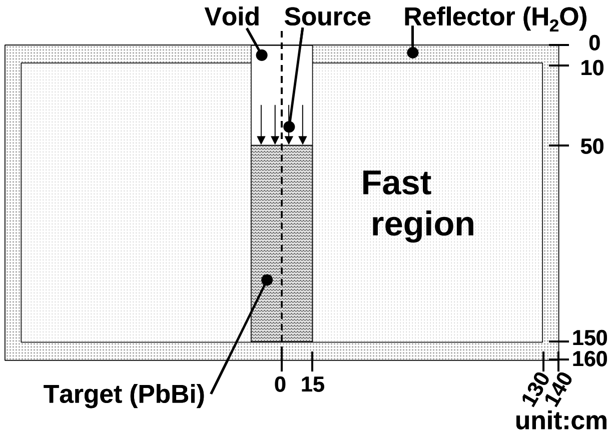

Fig. 6 Configuration of One-Section Reactor

3.1 Calculation Code

A Monte Carlo code, MCNPX, is used for criticality and source calculation of the cascade reactor and the one-section reactor. This code is developed at Los Alamos National Laboratory and can simulate spallation reaction by few GeV protons and fission reaction by neutrons and calculate neutron production. Therefore the cascade effect coefficient f can be estimated from source problem calculations of the cascade reactor and the one-section reactor.

3.2 Calculation Condition

Main calculation conditions are as follows.

Proton energy: 1.0GeV

Target: Pb-Bi

Coolant

Fast section: Pb-Bi

Thermal section: light water

Neutron absorber: Sm

The fast spectrum section is like a fast reactor whose coolant is Pb-Bi. The thermal section is similar to a pressurized water reactor. These specifications are not optimized and selected only to find the potential of the cascade reactor. Sm is chosen as a thermal neutron absorber because the thermal neutron capture cross sections of these isotopes are several ten thousands barn. The configuration of the cascade reactor is shown in Fig. 5 and the one-section reactor in Fig. 6. The one-section reactor has a subcritical fast spectrum core. Numerical calculation cases and calculated multiplication factors are shown in Table 1. Total subcriticality of the reactor is a parameter ranging from 0.01 to 0.09 so as to find a relation between the cascade effect coefficient and the subcriticality. Neutron multiplication factor of each section is assumed to be the same, which simplifies the problems.

Table 1 Numerical Calculation Cases

Case	Thickness of fast core (cm)	Thickness of absorber (cm)	Neutron Multiplication keff by MCNPX		
			Fast region k11	Thermal region k22	Cascade core
1	65	5	0.899	0.899	0.911
2	20	5	0.901	0.901	0.931
3	20	5	0.919	0.929	0.954
4	20	5	0.952	0.950	0.978
5	40	5	0.904	0.900	0.921
6	40	5	0.936	0.932	0.951
7	20	3	0.951	0.949	0.991
8	20	4	0.949	0.949	0.985
9	20	8	0.951	0.949	0.974

3.3 Calculation Process

Fig.7 shows the calculation flow for the cascade reactor. The calculation process is as follows. At first, the compositions of the two sections are decided so that each section has the same multiplication factor and the cascade reactor keeps subcriticality. For example, the enrichment of each section is adjusted so that the multiplication factor of each section is 0.90 and the subcriticality of the cascade reactor is near 0.05Δk. That is, three kinds of critical calculations are performed by MCNPX; the fast spectrum core, the thermal spectrum core and the cascade reactor.

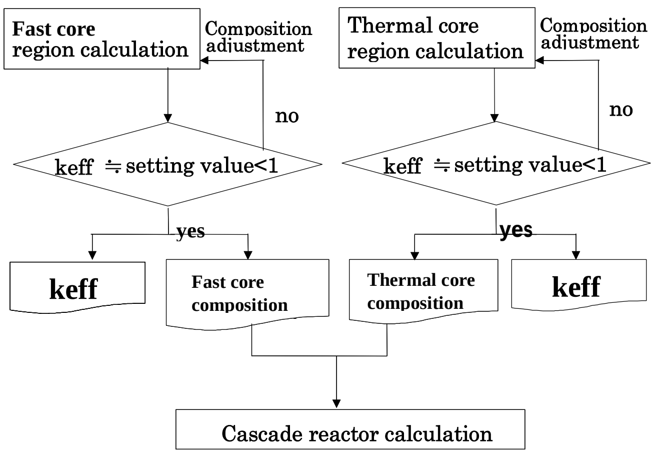

Fig.7 Calculation Flow for Cascade Reactor

Next, neutron behavior of the cascade reactor system is simulated using MCNPX and neutron production per proton is calculated. To compare with the cascade reactor, the same process is done for the one-section reactor that the outer diameter and the core height are the same as the cascade reactor. Its coolant and fuel are the same as the fast spectrum core and the enrichment is adjusted so that subcriticality is the same as the cascade reactor. MCNPX gives neutron production of the one-section reactor in a source problem calculation.

4. Numerical result for Cascade Reactor

4.1 Thickness of Fast Core

Since the leakage from the fast section to the thermal section seems important, the thickness of the Pb-Bi cooled section is changed so as to optimize the specification of the cascade reactor. The numerical results are shown in Fig. 8. When the thickness of core is changed from 65cm to 20cm and the subcriticality of each region is 10% Δk, the neutron multiplication factor of the cascade core becomes from 0.911 to 0.931. The number of produced neutrons is about 200 per a proton in the fast region and it becomes 50 to 250 in the thermal region. Although the produced neutron of one-section reactor with the same subcriticality increases, the cascade effect coefficient f becomes from 1.17 to 1.62. This trend is consistent with Fig. 3, that is, the cascade effect coefficient f enlarges, when the flow from the fast region to the thermal region becomes large.

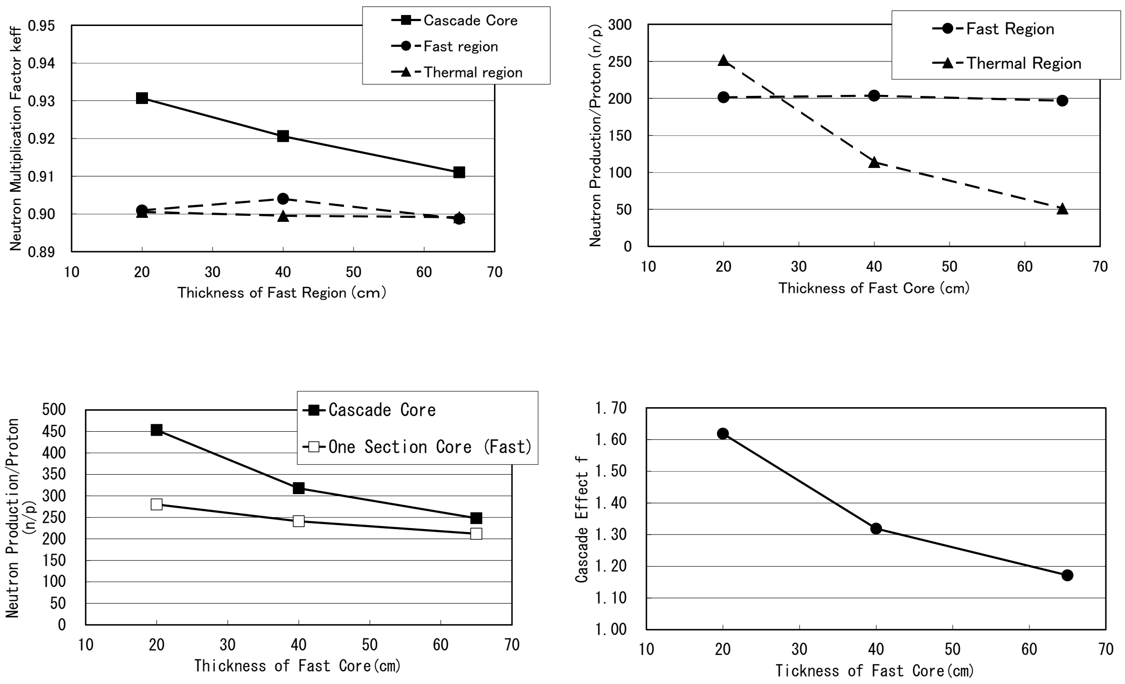

Fig. 8 Thickness of Fast Core and Neutron Multiplication Performance

4.2 Thickness of Thermal Neutron Absorber

The thickness of thermal neutron absorber is important because k12 and k21 depend on it strongly and their characteristics have an influence on the cascade effect. The numerical results are shown in Fig. 9. When the thickness of absorber changes from 8 cm to 5 cm and the subcriticality of each region is 5%Δk, the neutron multiplication factor of the cascade core shifts from 0.974 to 0.978 and the number of neutrons increases 820 to 1350 in the thermal region. The thickness of 5 cm is enough to absorb the thermal neutrons and the fast neutron can pass through it. When the thickness of absorber changes from 5 cm to 3 cm, the neutron multiplication factor increases from 0.978 to 0.991 and the number of neutrons increases 1900 to 3000 in the cascade core. When the thickness of absorber is not enough, the thermal neutrons flow from the thermal region to the fast region, the subcriticality reduces and the cascade effect coefficient f becomes small. As a result of the direct simulation, the thickness of Sm absorber should be about 5 cm so that the cascade effect coefficient f is 2.05.

The difference of neutron spectrum between both sections is important because it leads to asymmetry of neutron flow k21/k12 and causes the cascade effect. Fig. 10 shows k12 and k21 derived from the approximation equation, Eq. (5), using k11 and k22 in Table 1 and s0 =20. When the thickness of absorber becomes small, k21 increases by four times.

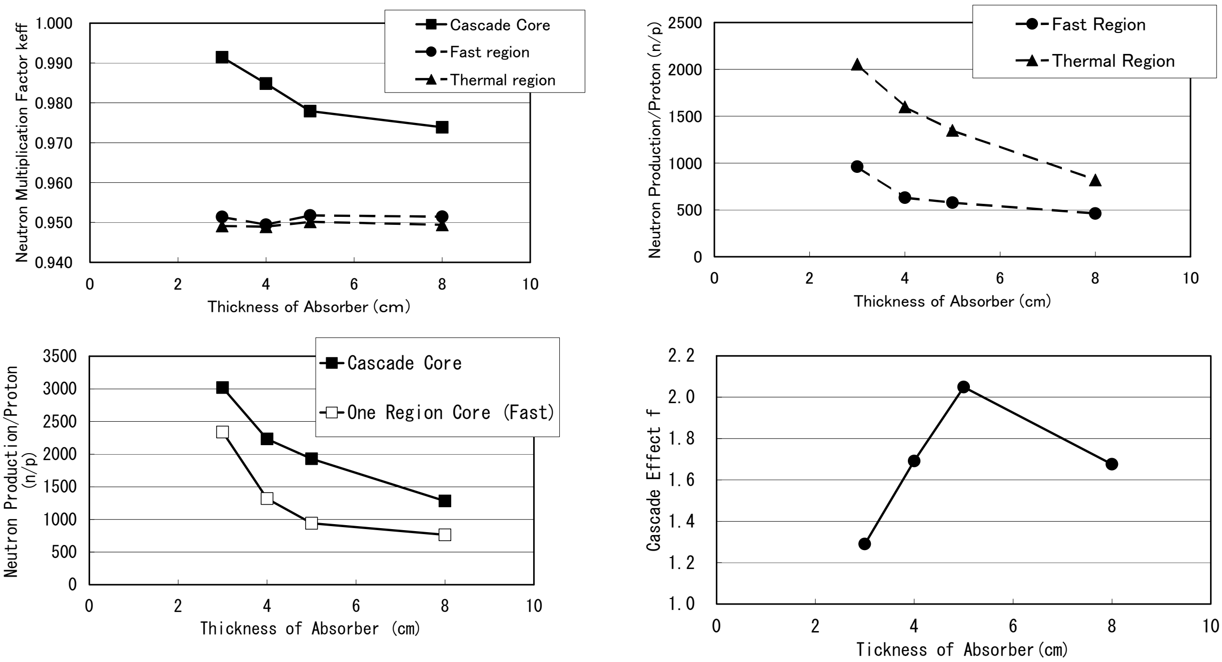

Fig. 9 Thickness of Fast Core and Neutron Multiplication Performance

4.3 Dependence of Cascade Effect on Subcriticality

Fig.11 shows that cascade effect increases when the subcriticality becomes small. This is consistent with the relation based on the theory, as shown in Fig. 4.

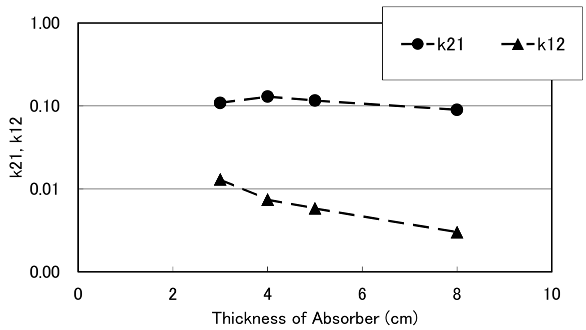

Fig. 10 Neutron Characteristics k12, k21

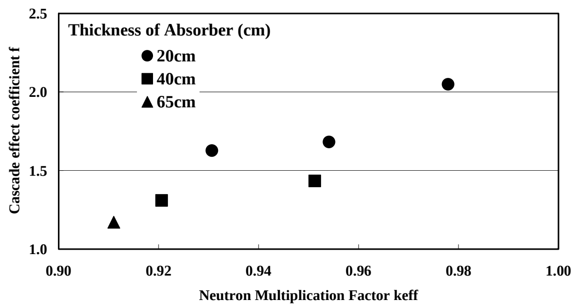

Fig.11 Dependency on Cascade Factor

5. Conclusion

It is confirmed that the cascade reactor can produce neutrons up to 2.05 times as many as the one-section reactor with the same subcriticality and the same neutron source strength. As a result of direct simulation by MCNPX, it is found that the thickness of fast core should be small to enhance the cascade effect, the thickness of absorber is optimized to be 5 cm and that cascade effect increases when the subcriticality becomes small. These results are consistent with the basic theory of coupling core.

Nomenclature

k, keff: effective multiplication factor of core
s: total neutron production of core
so: external neutron source
kij: multiplication factor in the i-th section for neutrons produced in the j-th section
i: section number, 1 is fast spectrum core, 2 is thermal spectrum core
ko: assumed that k11 = k22, k0 is defined that k11=k22=ko.

si: neutrons produced in the i-th section
Δk: subcriticality of core, Δk =1-k
Δki: subcriticality of each section, Δki =1-kii
f: cascade effect coefficient, neutron production ratio of cascade reactor to one-section core

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